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(54) Method and apparatus for attenuating engine generated noise.

(57) A method and apparatus are described for attenuating harmonic noise components contained within noise generated by an internal combustion engine (10), based upon the rotation of the engine (10) during its operating cycle. A signal representing selected multiple harmonic noise components is generated from a table of values, based upon the engine rotation. This signal is adaptively filtered to produce a cancelling waveform, which is superimposed onto the engine noise to attenuate the selected multiple noise harmonics. The method and apparatus are useful for selecting and attenuating dominant noise harmonics produced at different engine speeds or by different types of engines, and the dominant harmonics of different forms of noise produced by the same engine.

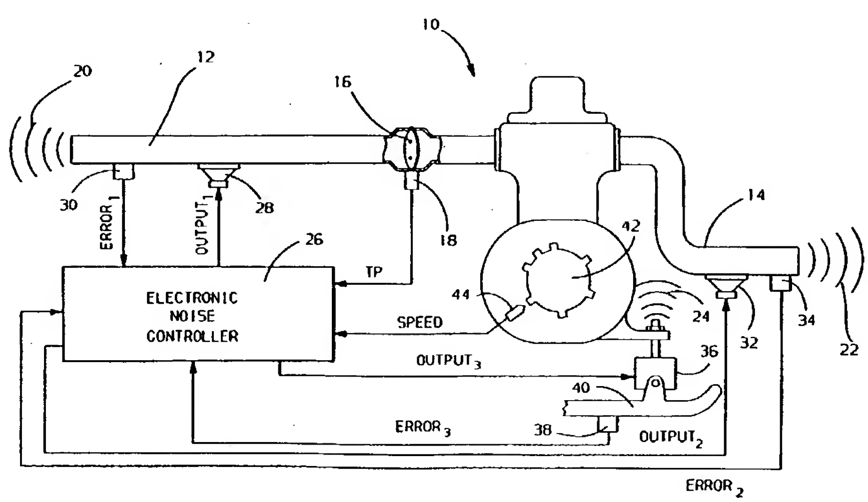

FIG. 1

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This invention relates to a method and apparatus for attenuating noise generated by an internal combustion engine.

Conventional active noise control systems attenuate undesirable noise, in the form of acoustic waves or mechanical vibrations propagating from a noise source, by producing and superimposing noise cancelling waves or vibrations, which are substantially equal in amplitude and frequency content, but shifted 180 degrees in phase with respect to the noise. Recently, this has been achieved through the use of modern digital signal processing and adaptive filtering techniques. Typically, an input sensor, such as a microphone or accelerometer, is used to measure the noise generated by the source, and to develop an input signal for an adaptive filter. This input is transformed by the adaptive filter into an output signal, which drives a speaker or actuator to produce cancelling waves or vibrations. An error sensor is employed to measure the observed noise level resulting from the superposition of the original noise and the cancelling waves or vibrations, and develops an associated error feedback signal. This feedback signal provides the basis for modifying the parameters of the adaptive filter to minimize the level of the observed noise.

In the past, such systems have been successfully applied to attenuate noise propagating down heating and air ventilating ducts. In these applications, the input sensor is placed upstream in the duct, followed by the cancellation actuator, with the error sensor positioned further downstream. The presence of a feedback path between the input sensor and the cancellation actuator in this type of system requires the use of a recursive type adaptive filter to model the acoustic channel and provide system stability. Although these systems are capable of cancelling both repetitive and random noise components, the necessity of a recursive adaptive filtering algorithm, as opposed to a non-recursive type, requires significantly more digital memory and processing time due to the increased computational complexity.

The acoustic and vibrational noise generated by an internal combustion engine differs significantly from that found in heating and air ventilating ducts. The amplitude of engine generated noise can vary quite rapidly with abrupt changes in engine loading, as for example, when the engine is quickly accelerated or decelerated. In addition, engine generated noise is dominated by harmonically related components having frequencies which vary as a function of the engine rotational speed. Also, engines having differing numbers of cylinders generate noise characterized by different dominant harmonic components, due to the different firing frequencies. Finally, acoustic and vibrational noise generated by an engine have different harmonic content, depending upon whether the source of the noise is the air intake system, the exhaust system, or mechanical vibrations produced by operation of the engine.

Consequently, a need exists for a convenient method of selectively attenuating the amplitudes of harmonic noise components generated by internal combustion engines.

The present invention seeks to provide an improved method and apparatus for attenuating engine noise.

According to an aspect of the present invention, there is provided a method of attenuating noise generated in an engine as defined in claim 1.

The invention can afford a convenient and flexible method of attenuating different dominant harmonic components produced by different types of engine, and from dissimilar noise sources in the same engine. Consequently, an active noise control system employing the present invention can be customized to meet the needs of the particular application, since system electrical power requirements, the cancellation actuator size, and system frequency response are directly related to the number and order of the harmonics selected for attenuation.

In an embodiment, a noise signal representative of selected harmonic noise components is generated from a predetermined schedule of values, based upon the angular rotation of the engine in the operating cycle. The values in the schedule may be determined by computing the sum of sinusoidal terms associated with the selected multiple harmonic noise components. The arguments of the sinusoidal terms may be functions of integer multiples of the angular position of the engine in its operating cycle. Thus, the generated noise signal can be automatically synchronized to the rotation of the engine, to assure correspondence between the frequencies of components contained within the generated signal and the noise harmonics produced by the engine.

In another embodiment, different schedules of values may be used when generating the noise signal, with each schedule corresponding to a specified range of engine speed. Values for each schedule can then be determined to correspond to the dominant harmonic noise components produced by the engine, when it operates within the specified range of speeds.

Thus, the present invention may be employed to effectuate the attenuation of engine noise which contains different order dominant harmonics, depending upon the operating speed of engine.

As contemplated by another embodiment, engine noise is attenuated by developing a noise cancelling waveform, and superimposing it onto the engine noise to be attenuated. The noise cancelling waveform preferably has substantially the same amplitude and frequency content as the noise to be attenuated, but is

shifted in phase by 180 degrees. In one practical embodiment, the cancelling waveform is developed by adaptively filtering the noise signal. In another practical embodiment, the noise signal is amplitude modulated, as a function of engine loading, prior to being adaptively filtered to develop the cancelling waveform. As a consequence, the method is capable of responding more rapidly to changes in the engine noise level caused by abrupt changes in engine loading.

In both of the above practical embodiments, a conventional input noise measuring sensor and associated circuitry are displaced on the basis of the noise signal. As a consequence, the feedback path between a cancellation actuator and input sensor is eliminated, along with the necessity of a recursive adaptive filtering algorithm. Thus, an important advantage is that non-recursive adaptive digital filtering algorithms, such as the Filtered X Least Mean Squares (LMS) type, can be employed when practicing the present invention. Not only are these non-recursive digital algorithms inherently more stable than the recursive kinds, they are computationally less complex, and require less memory and processing time to execute.

According to a preferred embodiment, the method is adapted to attenuate engine noise generated from various sources, such as acoustic noise from the exhaust system or air intake system and vibration noise produced by operation of the engine, on the basis of engine rotation in the operating cycle. This can be accomplished by utilizing separate schedules, and generating a different signal for each source of noise, such that each signal represents the harmonic components produced by the particular source of noise.

Consequently, the present invention can dispense with the requirement of distinct input sensors and circuitry for measuring the noise from each source, as would be the case in the conventional active noise control systems described previously.

As described in copending European Patent Application 91201872.8, the response of an active noise control system to abrupt changes in engine loading can be improved if the amplitude of the input signal representing the noise to be attenuated is modulated as a function of the load on the engine. Thus, in another embodiment of the present invention, the amplitude of the input signal generated to represent the multiple engine noise harmonics is modulated as a function of engine loading. Preferably an indication of engine loading is derived by measuring the position of the intake throttle valve, it should be understood that other measures of engine loading could be used, such as intake manifold vacuum or engine mass air flow.

According to another aspect of the present invention, there is provided apparatus for attenuating noise generated by an engine as defined in claim 11.

As will be apparent, the present invention is directed towards providing a convenient method and apparatus for selectively attenuating the amplitudes of harmonic noise components generated by an engine, and which can eliminate the necessity of the conventional input microphone, so that a more efficient non-recursive type adaptive filtering algorithm can be employed.

It will be recognized by those skilled in the art that the present invention can be used to attenuate a single form of engine generated noise, or several forms of engine noise simultaneously by applying the invention to each channel of a multi-channel electronic noise controller.

An embodiment of the present invention is described below, by way of illustration only, with reference to the accompanying drawings, in which:-

Figure 1 is a schematic diagram of an embodiment of active noise control system employed to attenuate engine generated noise;

Figure 2 is a block diagram representing electronic components of the noise control system of Figure 1, used for deriving an indication of angular rotation of the engine in the operating cycle;

Figure 3 is a flow diagram representative of the instructions in a routine executed by the noise control system of Figure 1, in generating a signal representative of multiple harmonic components contained within engine generated noise;

Figure 4 is a flow diagram representative of the instructions in a routine executed by the noise controller of Figure 1, in generating a signal representative of multiple harmonic components contained within engine noise, where the amplitude of the signal is modulated as a function of engine loading;

Figure 5 is a schematic diagram of a Filtered X Least Mean Squares (LMS) adaptive model utilized in the preferred embodiments of the present invention; and

Figure 6 is a schematic diagram representing the off-line training process for auxiliary filter E of the adaptive model illustrated in Figure 5.

Referring to Figure 1, there is shown schematically an internal combustion engine 10 having an associated air intake system 12 and exhaust system 14. A rotatable throttle valve 16 is included within the air intake system 12 for regulating air flow to the engine 10. Also shown are two sensors generally associated with the electronic control of the engine performance. The first sensor is a standard throttle position sensor 18, such as a potentiometer, which is connected to throttle valve 16 and develops an

electrical signal TP related to the degree or percent of throttle valve opening. The second is a conventional engine rotational sensor, which includes a toothed wheel 42 mounted on the engine crankshaft, and an electromagnetic sensor 44 that produces a SPEED signal having pulses corresponding to the movement of teeth on wheel 42 past electromagnetic sensor 44. The particular toothed wheel 42, shown in Figure 1, has six symmetrically spaced teeth producing equally spaced pulses in the engine SPEED signal, and a seventh asymmetrically spaced tooth than produces a synchronization pulse typically used for determining engine rotation from a known reference position.

During the operation of engine 10, acoustic pressure waves are generated and propagate away from the engine through the ducts and tubes forming the air intake and exhaust systems. Eventually, these pressure waves propagate from openings in the intake and exhaust systems as observable engine induction noise 20 and exhaust noise 22. In addition, the engine generates noise in the form of mechanical vibrations 24, which are ultimately transferred to a mounting frame 40 used to support engine 10.

Further illustrated in Figure 1 are components of an embodiment of active noise control system used for attenuating induction, exhaust, and vibrational noise generated by engine 10. Electronic noise controller 26 is a multi-channel device having three separate channels, with each channel operating independently to attenuate one of the different forms of engine noise.

Conventionally, each channel of noise controller 26 would require a separate input sensor for deriving a signal representative of the noise to be cancelled by that channel. However, with this embodiment, individual input sensors are not required, since the input signals for each channel can be generated from the engine rotational SPEED signal, as will be described subsequently.

As depicted in Figure 1, one channel of the noise controller 26 is utilized to attenuate the engine generated induction noise propagating inside the air intake system 12. Based upon an input signal associated with the engine induction noise, a cancelling OUTPUT signal is produced by noise controller 26. This OUTPUT signal drives a speaker 28, or any other type of suitable actuator capable of generating cancelling acoustic waves for superposition with the engine induction noise. An error microphone 30, or any other suitable acoustic sensor, is employed to measure the level of the attenuated induction noise remaining in the air intake system 12, after the superposition of the cancelling acoustic waves, and to develop a corresponding analogue $ERROR_1$ feedback signal. This $ERROR_1$ signal is directed back to the induction noise channel of the electronic noise controller 26, and provides the basis for minimizing the observed induction noise 20 propagating out of engine 10.

In using a second channel of the noise controller 26 to cancel exhaust noise, the operations described above are duplicated, except that a noise cancelling $OUTPUT_2$ signal is produced to drive the exhaust actuator or speaker 32, and an $ERROR_2$ signal is developed by microphone 34 to act as feedback for the exhaust noise channel of noise controller 26.

Similarly, in cancelling engine generated vibrational noise 24, a third channel of the noise controller 26 produces noise cancelling signal $OUTPUT_3$ to drive an electromagnetic shaker 36, which is disposed between engine 10 and mounting frame 40. Electromagnetic shaker 36 may be any type of actuator known to those skilled in the art, as for example, a commercially available Model 203B Shaker supplied by Ling Electronics, Inc., which is capable of producing the required out-of-phase cancelling vibrations. Also, an error feedback signal $ERROR_3$ representing the residual vibrations transferred to mounting frame 40 is developed by an error sensor 38, such as an accelerometer, which is attached to the mounting frame 40.

The electronic noise controller 26 preferably includes a standard digital signal processor and the necessary interfacing circuitry such as analogue amplifiers and filters, analogue-to-digital and digital-to-analogue converters, frequency multipliers, counters, clocks, and other known input/output signal conditioning circuitry. The actual hardware implementation of noise controller 26 is not described herein, since such circuitry is well known in the art and is described in numerous publications and texts, see for example, "Hardware and Software Considerations for Active Noise Control", M. C. Allie, C. D. Bremigan, L. J. Eriksson, and R. A. Grainier, 1988, IEEE, CH 2561-9/88/0000-2598, pp. 2598-2601.

Digital signal processors are commercially available, for example the Motorola 56000, and typically contain a central processing unit for carrying out instructions and arithmetic operations, random access memory for storing data, and read only memory for permanently storing program instruction. When utilized for active noise control, the digital signal processor is typically programmed to function as a single adaptive digital filter. In the above described application, the digital signal processor is programmed to function as a multi-channel device, with each channel having a separate adaptive filter.

The amplitudes of the various analogue signals directed to the noise controller 26 are sampled at a fixed sampling rate and sets of these sample values are retained for use in computing digital output signals using the adaptive filtering algorithms of the separate channels. The digital output signals are then converted to analogue form and appropriately amplified to provide the signals necessary for driving the

system cancellation actuators.

The method used in generating the input signals for different channels of the noise controller 26 will now be described. In the preferred embodiments of the invention, an indication of the angular rotation of the engine is derived from the engine SPEED signal produced by the engine rotational sensor described previously, however, any other known means for sensing engine rotation could also be employed.

The block diagram shown in Figure 2 represents circuitry within noise controller 26 used to process the engine SPEED signal. The SPEED signal, which contains pulses generated by the movement of toothed wheel 42 past electromagnetic sensor 44, is passed to the conditioning circuitry 46, where the asymmetrical synchronization pulse is eliminated and the remaining symmetrical pulses are shaped to be compatible with the digital format of the noise controller 26. These formatted digital pulses representing crankshaft angular rotation are then passed to a standard frequency multiplier/divider, which generates a fixed number of pulses during one complete rotation of the engine crankshaft. These pulses are then counted by a conventional modulo counter, to provide an output COUNT signal, which is indicative of the rotational position of the crankshaft in the engine cycle at any given time.

In general, the number of teeth on wheel 42, the frequency multiplier/divider, and the modulo counter are selected to provide an integer count ranging in value from 0, to a maximum value of MAX, each time the engine completes a cycle, which in a four-stroke engine is two full revolutions of the engine crankshaft. The value of COUNT thus represents a derived indication of the angular rotation of the engine in the operating cycle. Based upon the value of COUNT, the noise controller 26 is able to generate a separate input signal for each channel representing the multiple harmonic components selected for attenuation of noise associated with that particular channel.

To avoid unnecessary duplication in this description, in what follows only a single channel of noise controller 26 will be described using generalized terms for the channel signals, such as OUTPUT and ERROR, without reference to the subscripted terms shown in Figure 1. It should then be understood that this description will be equally applicable to any of the individual channels of the noise controller 26.

Referring now to Figure 3, there is shown a flow diagram representative of the program steps that would be executed by electronic noise controller 26 in one embodiment of the present invention, in generating a channel input signal representing multiple harmonic components selected for attenuation. The Input Signal Generating Routine is entered at point 52, after each system interrupt associated with the sampling rate of the digital signal processor contained within electronic noise controller 26. The program then proceeds to step 54, where the current COUNT of the previously described modulo counter is read and stored. As described later, it may also be desirable at this step to establish a value for RPM, the rotational speed of the engine. This may be accomplished, for example, by storing consecutive values of COUNT at specified times established by an interval timer, and then subtracting these stored values to obtain the angular rotation of the engine during the timer interval. The current value representing RPM can then be determined by multiplying the resulting angular rotation of the engine by a fixed scaling constant to convert to revolutions per minute.

Next at step 56, INPUT, a sample value for the input signal representing multiple harmonic noise components selected for attenuation, is looked up in an INPUT table containing a schedule of values that vary as a function of the COUNT found in the previous step 54. Stored values the INPUT table schedule are computed on the basis of the following general equation:

$$\mathrm{INPUT} = A \sin(q{*}\mathrm{COUNT}) + B \sin(2{*}q{*}\mathrm{COUNT}) + C \sin(3{*}q{*}\mathrm{COUNT}) + \ldots + M \sin(m{*}q{*}\mathrm{COUNT}), \qquad (1)$$

where, A, B, C, ... , and M represent the amplitudes of the harmonic components used in approximating the engine noise; q is a conversion constant given by $q = 2\pi/(\mathrm{MAX}+1)$; and the integer m represents the order of the largest harmonic related to engine rotational speed that is of interest.

For the purpose of computing values for the INPUT table, a form of noise produced by a given engine is measured to determine the order of the dominant harmonic components present within the noise. Next, the amplitudes A, B, C, ..., and M of the harmonic components in the above equation, which are selected to be attenuated in the engine noise, are set equal to unity, and the amplitudes of those not selected for attenuation are set to zero. Then, table values for INPUT are computed for each possible integer value of COUNT, using the equation presented above. Prior to storage in the table, all of the calculated INPUT values are normalized to range between -1 and 1, by dividing each by the maximum magnitude found for the table INPUT values. Alternatively, relative values for the amplitudes A, B, C, ..., and M of the selected noise harmonics could be found by measuring the noise to be attenuated and determining an average amplitude value for each harmonic component, while running the engine on a dynamometer at different speeds over the operating range of the engine.

In applications where different order noise harmonics are dominant at different engine operating speeds, the INPUT table can contain different schedules for different ranges of engine operating speed. The values for each separate schedule can then be computed, as described above, to correspond to the dominant noise harmonics produced by the engine, when it operates within the associated range of engine speed. For this particular embodiment of the invention, the current engine speed, as represented by the value of RPM derived in step 54, is used to select the appropriate INPUT table schedule, from which a sample for the input signal is looked up, based upon the current value of COUNT. Thus, there is provided a convenient and flexible technique for selecting which engine noise harmonics are to be attenuated by the active noise control system for a particular form of noise and engine type. This technique also enables the active noise control system to be customized to meet the needs of the particular application, since system electrical power requirements, the cancellation actuator size, and system frequency response are directly related to the number and order of the harmonics selected for attenuation.

From step 56 the program proceeds to step 64, where the value for INPUT is stored in memory as INPUT(n), which represents the most recently generated sample value for the INPUT signal. Prior to storing this new value for INPUT(n), the previous value is shifted and stored in memory as INPUT(n-1), and so forth down to the last retained sample in the sequence INPUT(n-N+1), where N represents the number of sequential sample values of the INPUT signal retained in memory for later use by the noise controller 26.

Then at step 66, the routine is exited with the sequence of generated INPUT samples acting as a channel input signal representing the multiple harmonic noise components selected for attenuation by that channel of the noise controller 26. Because the generation of the input signal is based upon the current value of COUNT from the modulo counter, the input signal is automatically synchronized to the rotation of the engine, which assures correspondence between the frequencies of components contained within the generated signal and the noise harmonics produced by the engine.

In another embodiment, the amplitude of the input signal generated to represent the multiple engine noise harmonics is modulated as a function of engine loading (derived by measuring the position of the throttle valve 16, or intake manifold vacuum or engine mass air flow), in the manner described in copending application no. 91201872.8.

Referring now to Figure 4, there is shown a flow diagram representing the program steps that are executed by noise controller 26, when generating a channel input signal that has its amplitude modulated as a function of engine loading. Note that corresponding steps in the flow diagrams of Figures 3 and 4 have been designated with the same numerals.

The Modulated Input Signal Generating Routine is entered at step 68 and proceeds through the same steps 54 and 56, previously described in conjunction with Figure 3, to look up a sample value for INPUT.

Next at step 70, noise controller 26 reads the current position of the throttle valve by sampling the value of the analogue throttle position signal TP. This value for TP is stored, and the program then proceeds to step 72.

At step 72, a value for MOD, the modulation factor, is looked up in a stored schedule, as a function of the current position of the throttle found in step 70. The schedule values for the modulation factor MOD will be dependent both upon the form of the noise and the type of engine producing it. Values for the MOD table can be determined by measuring the particular form of noise to be attenuated, while operating an engine on a dynamometer. The value representing MOD for each position of the throttle are found by determining the average level of noise produced, while varying engine speed with the throttle position fixed. All such measured average values are normalized prior to storage in the MOD schedule, by dividing each average value by the maximum average value found during testing. In this way, the stored values in the MOD schedule are scaled to range between 0 and 1.

Next at step 74, a new amplitude modulated value for INPUT is computed by multiplying $INPUT_{-1}$, the value of INPUT found at step 56, by the modulation factor MOD found at step 72.

Then as in Figure 3, the routine proceeds to step 64, where the current value for INPUT is stored in memory as INPUT(n), which represents the most recently generated sample value for the amplitude modulated INPUT signal. As previously described, prior to storing this new value for INPUT(n), the previous value is shifted and stored in memory as INPUT(n-1), and so forth down to the last retained sample in the sequence INPUT(n-N+1).

The routine is exited as step 66, with the sequence of generated INPUT samples representing a channel input signal, which has its amplitude modulated as a function of engine loading.

A sequence of sample values representing the input signal for a particular channel of the noise controller 26 can thus be derived using either of the routines of Figures 3 and 4. A corresponding sequence of sample values ERROR(n), ERROR(n-1), ... , ERROR(n-N+1), is obtained for each channel by sampling each channel's analogue error signal at the system sampling rate and then stored in the memory of the

noise controller 26. Using these sample values for the channel input and error signals, noise controller 26 computes a sample value OUTPUT(n) for the channel output signal using an adaptive filtering algorithm. The noise controller 26 converts the consecutively computed digital samples OUTPUT(n) into an analogue waveform, which is then amplified to produce the OUTPUT cancelling signal used to drive the channel's cancellation actuator.

As previously indicated, one of the advantages associated with the above embodiments is the elimination of the need for separate channel input sensors for measuring each form of engine noise to be attenuated by the separate channels of the noise controller 26. As a consequence, the conventional feedback path between the traditional input sensor and the cancellation actuator is eliminated, and non-recursive type adaptive filtering algorithms can then be used to compute the channel OUTPUT(n) samples. Not only are these non-recursive digital algorithms inherently more stable than the recursive types, they are computationally less complex, and require less memory and processing time to execute.

Referring now to Figure 5, there is shown a schematic diagram for a Filtered X Least Mean Squares (LMS) adaptive filter, which is the type of non-recursive filtering algorithm utilized for the preferred embodiments of the present invention. Only a brief explanation of the operation of this particular type of adaptive filter will be provided here, as a detailed description can be found in the text book Adaptive Signal Processing, B. Widrow and S. Sterns, Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 1985, pp. 288-294. Although each channel of the noise controller 26 has a separate adaptive filter, only one such filter is described below, since the description is applicable to each channel.

Consecutive sample values for a channel OUTPUT(n) signal are produced at the system sampling rate, by adaptively filtering the most recent INPUT(n) sample, and the other retained samples in the INPUT sequence, using the non-recursive digital A filter 76. New sample values for OUTPUT(n) are computed on the basis of the following algorithm:

$$\mathrm{OUTPUT}(n) = \sum_{i=0}^{N-1} A_i(n) * \mathrm{INPUT}(n-i), \qquad (2)$$

where the set $A_i(n)$ represents the most recently computed adaptive filter coefficients for the A filter, and N represents the size of the filter, as well as the number of samples of generated input signal retained in memory.

After a new sample value is computed for OUTPUT(n), the adaptive filter coefficients $A_i(n)$ are updated as indicated by the UPDATE A block 77 in the diagram, in order to minimize the ERROR(n) sample values, which represent the residual engine noise remaining after the superposition of the cancelling noise waveform. The UPDATE A block 77 has two inputs, the first being ERROR(n), and the second being a filtered sequence of sample values designated as INPUT'(n) derived by passing the corresponding sequence of input signal samples INPUT(n) through the auxiliary E filter 78. The algorithm for updating each of the adaptive filter weights $A_i(n)$ to $A_i(n+1)$, for the next sampling interval is given by:

$$A_i(n+1) = g * A_i(n) - u * \mathrm{ERROR}(n) * \mathrm{INPUT}'(n-i), \qquad (3)$$

where g represents the filter leakage coefficient having a value in the range of $0 << g < 1$, and u represents the filter convergence factor having a value in the range of $0 < u << 1$. For the present invention the preferred values for g and u were $g = 0.999$ and $u = 0.03$.

The sequence of sample values for the INPUT'(n) signal in equation (3) are obtained by filtering the sequence of INPUT(n) values with the auxiliary E filter 78 on the basis of the following equation:

$$\mathrm{INPUT}'(n) = \sum_{i=0}^{N-1} E_i(n) * \mathrm{INPUT}(n-i), \qquad (4)$$

where $E_i(n)$ represents the fixed weighting coefficients for the auxiliary E filter. As described in " An Analysis of Multiple Correlation Cancellation Loops with a Filter in the Auxiliary Path", D. R. Morgan, IEEE Transactions on Acoustic Speech Speech Signal Processing, Vol. ASSP-28, No. 4, 1980, pp.454-467, the

auxiliary E filter 78 is used to compensate for the distortion produced by components in the channel error path of the active noise control system. This error path typically includes the channel cancellation actuator and the associated output circuitry within noise controller 26; the error sensor and the associated error input circuitry within noise controller 26; and the characteristics of the physical path between the channel cancellation actuator and error sensor, over which the engine noise propagates.

Referring now to Figure 6, there is shown a schematic diagram representing the process used in calibrating a channel auxiliary E filter 78 to obtain its fixed weighting coefficients. In this process, the auxiliary E filter is calibrated to have a transfer function equivalent to the combined components in the channel error path. When calibrating an E filter for a particular channel of the noise controller 26, the components in the error path, such as the cancellation actuator 82, noise propagation path 84, and error sensor 86, must remain in the same physical locations, as when they are used in attenuating the engine noise associated with that channel.

The calibration process uses a conventional RANDOM NOISE SOURCE 80 to generate a sequence of random signal values designated as IN(n). The random signal samples are directed as input to the auxiliary E filter 78, and are also passed through the components of the error path to produce a corresponding sequence of samples designated as D(n). In passing over the error path, the IN(n) samples are subjected to the same components as are the OUTPUT(n) samples and the resulting ERROR(n) samples of Figure 5.

For the calibration configuration shown in Figure 6, the algorithms associated with the digital E filter 78, and its adaptation by the UPDATE E block 88, are given by:

$$OUT(n) = \sum_{i=0}^{N-1} E_i(n) * IN(n-i), \text{ and} \qquad (5)$$

$$E_i(n+1) = g * E_i(n) + u * ERR(n) * IN(n-i), \qquad (6)$$

where, OUT(n) represents sample values output by the digital E filter 78, and ERR(n) samples produced as output from summer 89 which are given by:

$$ERR(n) = D(n) - OUT(n), \qquad (7)$$

where D(n) represents the sample values derived from the channel error sensor 86. With this calibration process, the weighting coefficients of the digital E filter 78 are adaptively updated to minimize the ERR(n) values. When this adaptive modelling procedure is complete, the transfer function of the digital E filter 78 duplicates that of the combined components in the channel error path, and can be used as illustrated in Figure 5 to compensate for the distortion introduced by components in the system error path.

Although the Filtered X Least Mean Squares (LMS) adaptive filter has been described as the preferred type of non-recursive adaptive filter used in the preferred embodiments, it should be understood that other types of adaptive filters, recursive as well as non-recursive, may also be used.
However, the computational efficiency associated with the Filtered X Least Mean Squares (LMS) adaptive filter permits a single digital signal processor to be programmed to function as a multi-channel device so that more than one form of engine noise can be attenuated with a single noise controller.

Claims

1. A method of attenuating noise generated in an engine, which noise is related to engine rotational speed, comprising the steps of deriving an engine position signal indicative of the rotational position of the engine in an operating cycle; generating a noise signal representative of selected harmonic noise components on the basis of the engine position signal; and attenuating noise generated by the engine on the basis of the noise signal.

2. A method according to claim 1, wherein the noise signal is generated from a predetermined schedule of values as a function of the engine position signal, the values in the schedule being determined by summing separate sinusoidal terms, each sinusoidal term corresponding to a selected harmonic component and having an argument related to an integer multiple of the engine position.

3. A method according to claim 1, comprising the step of deriving an engine speed signal indicative of the engine rotational speed; the noise signal being generated on the basis of the engine position signal and the engine speed signal.

4. A method according to claim 3, wherein the noise signal is generated from a table comprising a plurality of predetermined schedules, each schedule being associated with a different engine rotational speed and including values determined by summing separate sinusoidal terms, each term corresponding to a selected harmonic component for the associated engine speed and having an argument related to an integer multiple of the engine position.

5. A method according to any one of claims 1 to 4, wherein the step of attenuating noise generated by the engine includes the steps of developing a noise cancelling waveform by adaptively filtering the noise signal; and superimposing the noise cancelling waveform on the noise generated by the engine.

6. A method according to claim 5, wherein the noise signal is adaptively filtered using a Filtered X Least Mean Squares (LMS) algorithm.

7. A method according to any one of claims 1 to 4, wherein the step of attenuating noise generated by the engine includes the steps of deriving an indication of engine loading; modulating the amplitude of the noise signal as a function of engine loading; developing a noise cancelling waveform by adaptively filtering the amplitude modulated noise signal; and superimposing the noise cancelling waveform on the noise generated by the engine.

8. A method according to claim 7, wherein the amplitude modulated noise signal is adaptively filtered using a Filtered X Least Mean Squares (LMS) algorithm.

9. A method according to any preceding claim, wherein the harmonic noise components selected for attenuation are acoustic noise propagating from the engine.

10. The method of claim 1, wherein the multiple harmonic noise components selected for attenuation propagate from the engine in the form of mechanical vibrations.

11. Apparatus for attenuating noise generated in an engine, which noise is related to engine rotational speed, the apparatus comprising speed deriving means (42-50) for deriving an engine position signal indicative of the rotational position of the engine (10) in an operating cycle; processing means (26) for generating a noise signal representative of selected harmonic noise components on the basis of the engine position signal; and attenuating means (28,32,36) for attenuating noise generated by the engine on the basis of the noise signal.

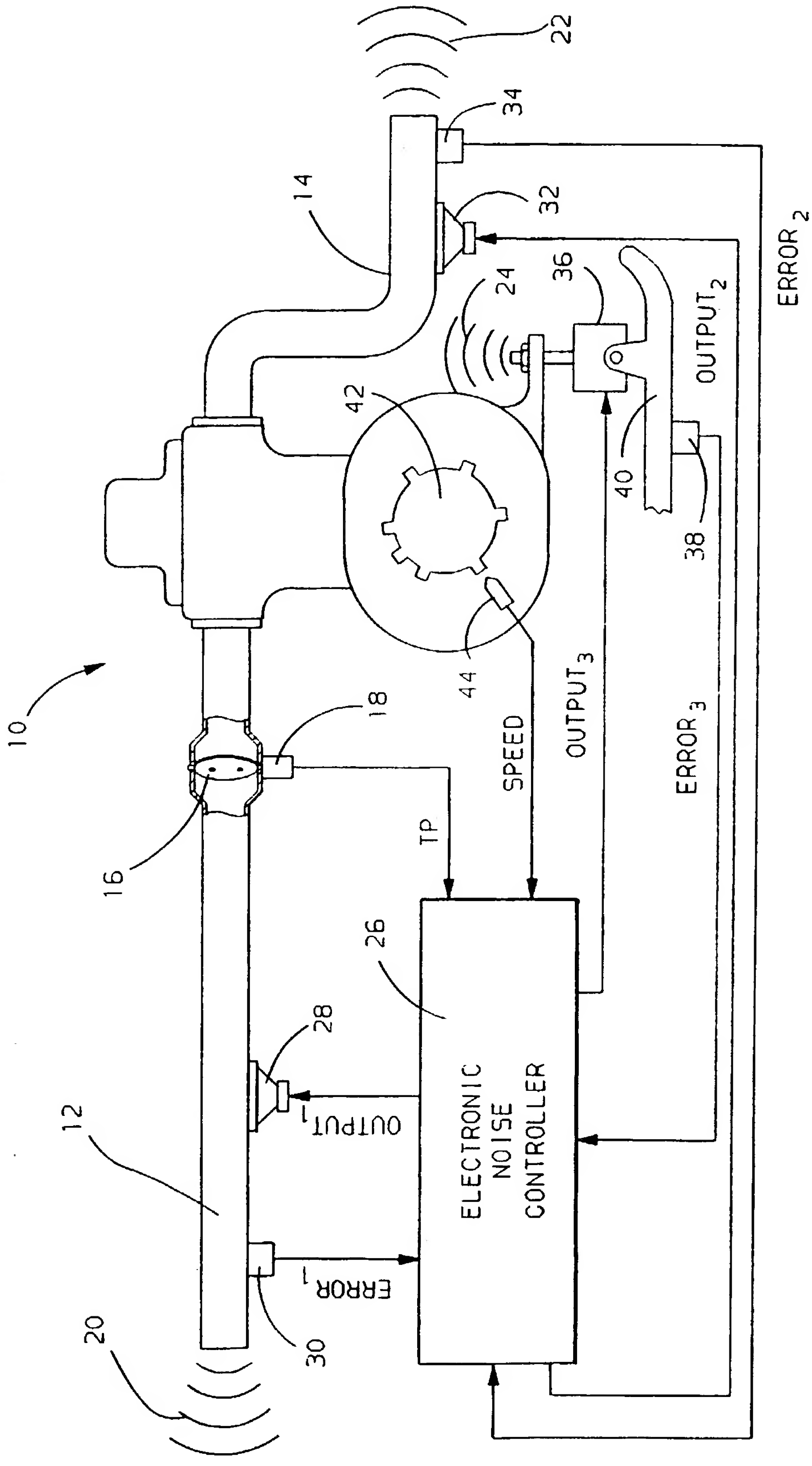
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
TP
SPEED
OUTPUT$_3$
ERROR$_3$
OUTPUT$_2$
ERROR$_2$
OUTPUT$_1$
ERROR$_1$
ELECTRONIC
NOISE
CONTROLLER

FIG. 1

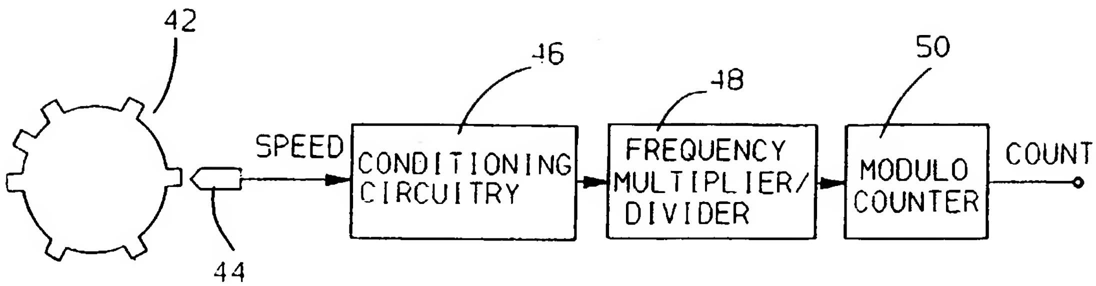

FIG.2

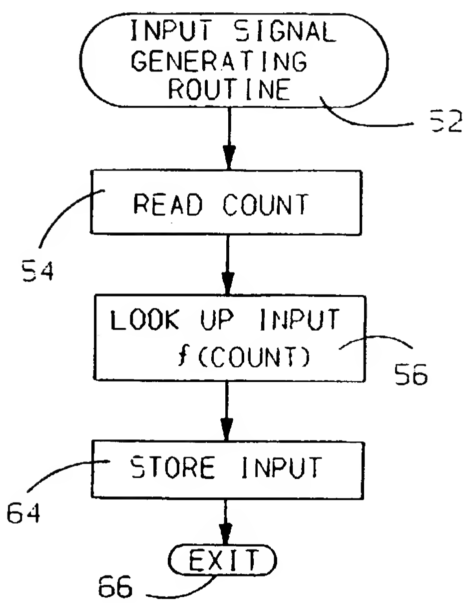

FIG.3

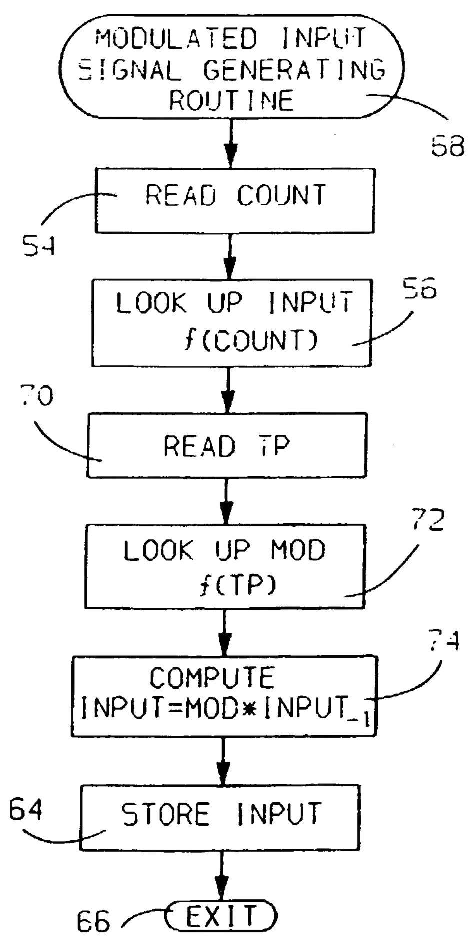

FIG.4

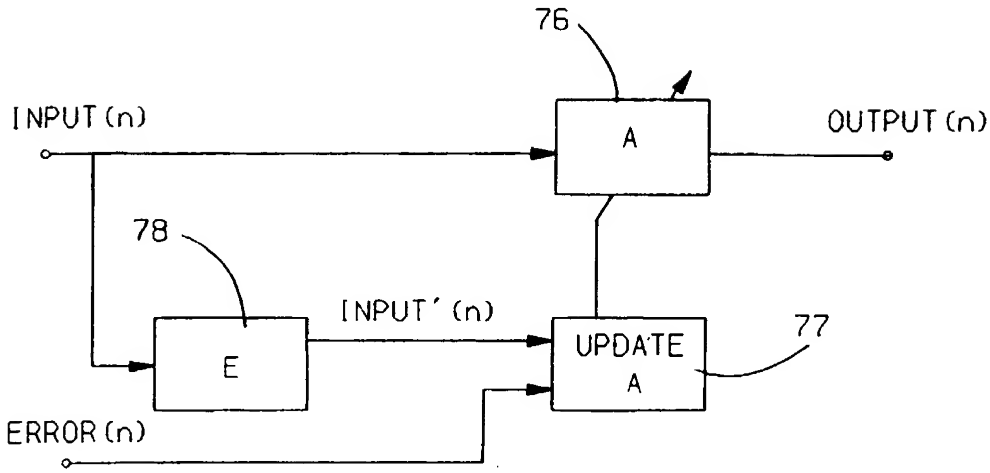
76
INPUT (n)
A
OUTPUT (n)
78
INPUT' (n)
E
UPDATE
A
77
ERROR (n)

FIG.5

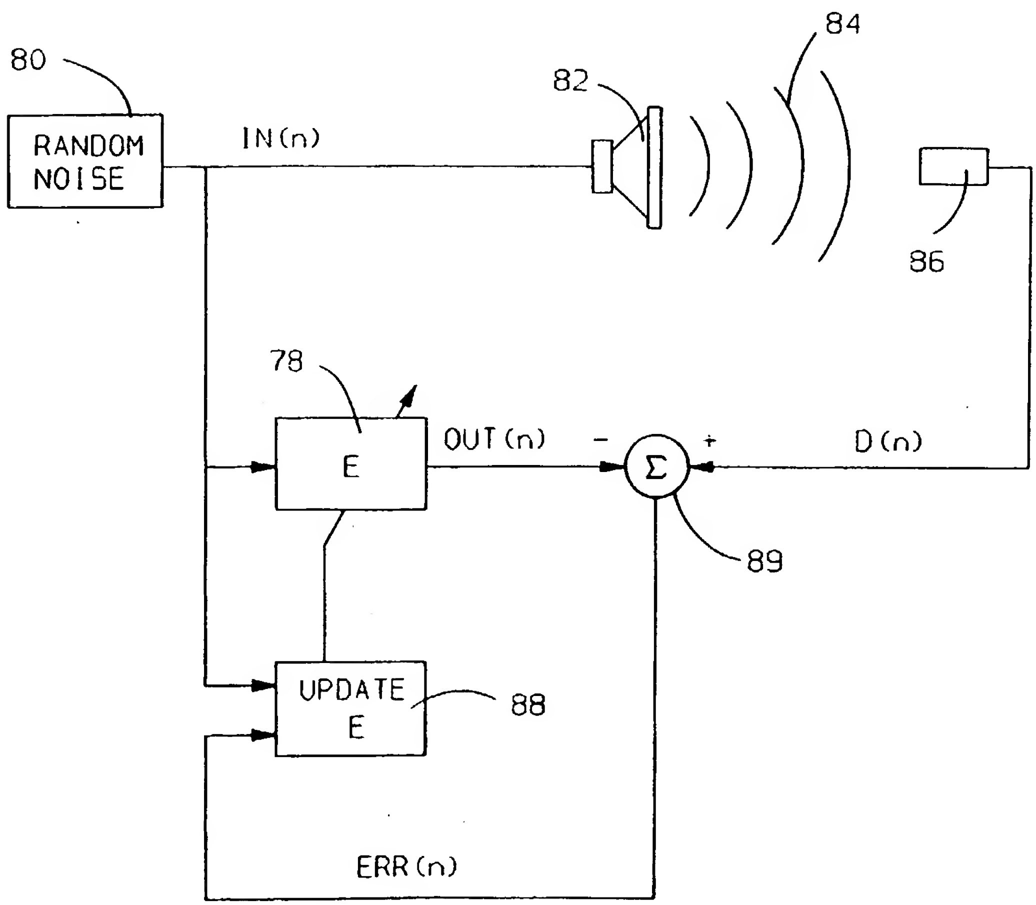
80
84
82
RANDOM
NOISE
IN (n)
86
78
E
OUT (n)
−
Σ
+
D (n)
89
UPDATE
E
88
ERR (n)

FIG.6